INL/CON-06-01092
PREPRINT

Effects of Interstage Cooling on Brayton Cycle Efficiency

ANS Annual Meeting

Chang H. Oh
Robert Barner

June 2006

Effects of Interstage Cooling on Brayton Cycle Efficiency

Chang H. Oh[1] and Robert Barner[2]

1. *Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3890, chh@inel.gov*
2. *Summer Intern, Texas A&M University, Department of Nuclear Engineering 3133 TAMU, College Station, TX 77843-3133*

INTRODUCTION

The US Department of Energy is investigating the use of high-temperature gas-cooled reactors (HTGR) [Oh,2005] to produce electricity and hydrogen. In anticipation of the design, development and procurement of an advanced power conversion system for HTGR, this study was initiated to identify the major design and technology options and their tradeoffs in the evaluation of power conversion system (PCS) options to support future research and procurement decisions. These PCS technology options affect cycle efficiency, capital cost, system reliability and maintainability and technical risk, and therefore the cost of electricity from Generation IV systems. In this study, we investigated the effect of interstage cooling in the PCS and present some results.

INTERSTAGE COOLING IMPACT

Interstage Cooling (IC) is an attractive option for improving the efficiency of the HTGR PCS. As additional stages are added, the average temperature over which input energy is added stays higher and/or the average temperature over which rejection energy is removed stays lower. If this were the only impact of the IC, the cycle efficiency would always increase with more stages. But with each additional stage, pressure drop is present. Additional interstage pumping must be accomplished to make up for this additional pressure drop. Because the pumps are not 100% efficient, eventually the entropy loss during an additional pumping operation results in a smaller total energy input than without that stage. When this occurs, the cycle efficiency actually decreases. When the cycle efficiency improvement is not justified for the additional cost, the additional stage can be assessed based upon achievable component performances.

Cycle efficiencies as well as differential cycle efficiencies (efficiency improvement per stage) were examined as a function of the number of input and rejection stages for several cycles including:

- Recuperated Helium Brayton cycle
- Recuperated 80% N_2 20% He (by weight) Brayton cycle
- Recuperated Supercritical CO_2 Brayton with split flow cycle
- Implication of gas or liquid intermediate loop
- Implication of IC to system layout

RESULTS

To determine the effects interstage cooling on cycle efficiency 1, 2 and 3 intercoolers were added to the basic indirect recuperated Helium and N_2/He mixture cycles. The pressure drop through the precooler was set at 20 kPa. With a 1-intercooler layout the intercooler pressure drop was set to 50 kPa. With 2 intercoolers the first intercooler pressure drop was set to 37 kPa and the second intercooler set to a pressure drop of 50 kPa. With a 3-intercooler layout the first, second and third intercooler pressure drops were set to 30, 40 and 50 kPa, respectively. These pressure drops were chosen because they are representative of pressure drops used by a MIT studied on an indirect Helium Brayton cycle with a maximum system pressure of 8 MPa [Wang, 2003].

A base design for each cycle was determined and input into HYSYS [Aspentech, 2000]. HYSYS was then used to simulate and optimize each cycle.

- Recuperated Helium Brayton cycle

The base cycle used in for this study was the indirect Helium cycle and operating conditions used in this section are summarized in Table 1. The efficiency without intercooling was 45.19%. The efficiency with 1, 2 and 3 intercoolers was 48.25%, 48.92% and 49.07%, respectively.

- Recuperated 80% N_2 20% He (by weight) Brayton cycle

The base cycle used in for this study was the indirect N_2/He cycle and conditions used in this section are shown in Table 1. The efficiency without intercooling was 45.29%. The efficiency with 1, 2 and 3 intercoolers was 49.39%, 50.19% and 50.47%, respectively.

- Recuperated Supercritical CO_2 Brayton with split flow cycle

Condition	Value
Reactor Power	600 MW
Reactor Outlet Temp	900 C
Turbine Polytropic Efficiency	92%
Compressor Polytropic Efficiency	90%
IHX Effectiveness	90%
Recuperator Effectiveness	95%
IHX Primary Side Pressure Drop	150 kPa
IHX Secondary Side Pressure Drop	175 kPa
Recuperator Hot Side Pressure Drop	90 kPa
Recuperator Cold Side Pressure Drop	50 kPa
Precooler Pressure Drop	20 kPa
Intercooler Pressure Drop	30 kPa
Compressor Inlet Temp	28 C
Pressure Ratio	2.1

Table 1. Cycle conditions.

The base design chosen for the supercritical CO_2 was developed at MIT [Dostal et al., 2004]. Split flow is an option for improving cycle efficiency when the working fluid is operated near its critical point. Around the critical point the fluid properties vary greatly. To take advantage of this the flow is split and a portion goes to a precooler before entering the compression stage. By compressing around the critical point the compressor work can be significantly reduced.

The model developed at MIT was repeated in HYSYS to ensure consistency between the two models. The MIT model with a 600 MW(t) reactor power and a 700 °C reactor outlet temperature was simulated in HYSYS. The MIT model gave a cycle efficiency of 51.3% and the HYSYS model gave an efficiency of 51.1%. Since the models were comparable the base model was then modified in HYSYS. The MIT design was modified to be an indirect cycle with a reactor outlet temperature of 867 °C. Next the heat flow in the IHX was set to 600 MW(t) to be consistent with the amount of power supplied to the PCS.

The HYSYS optimized recompression cycle produced a cycle efficiency of 52.09% compared to the 51.1% for the base model. Although this cycle has a slightly higher efficiency, it may not be advantageous from the point of additional capital costs and the potential material problems due to the higher temperatures to consider this options at the present time.

- Implication of bottoming cycles

A steam bottoming cycle can be used to further improve the efficiency of a cycle. The base design studied here was the Framatome cycle [Copsey, 2004]. The cycle efficiency of the combined cycle produces 49.56% due to the reduced pumping work for water in the Rankin cycle.

- Implication of interstage heating and cooling to system layout

Comparing the results of additional intercoolers as seen in Table 2, after the first intercooling stage is added, additional stages result in much smaller efficiency increases,. This decreasing efficiency gain is due to the additional pressure drop incurred by adding intercoolers. Eventually the efficiency increase from adding an intercooler will be off set by the additional cost of the intercooler. At that point the addition of another intercooler is not feasible.

Cycle layout	Cycle Efficiency	Differential Efficiency Gain
He Indirect no IC	45.19%	N/A
He Indirect 1 IC	48.25%	3.06%
He Indirect 2 IC	48.92%	0.67%
He Indirect 3 IC	49.07%	0.15%
N_2/He Indirect no IC	45.29%	N/A
N_2/He Indirect 1 IC	49.39%	4.10%
N_2/He Indirect 2 IC	50.19%	0.80%
N_2/He Indirect 3 IC	50.47	0.28
CO_2 Split Flow	52.09	N/A
N_2/He Indirect with a Combined Cycle	49.56	N/A

Table 2. Comparison of cycle implication due to various cycle layouts and intermediate cooling.

CONCLUSIONS

Intercooler increases the cycle efficiency due to lowering the inlet temperature to the compressor. A single intercooler improves the cycle efficiency by approximately 3 %. Once the first intercooler is used, the second and third intercooler provides much smaller efficiency increases.

ACKNOWLEDGMENT

This work was supported through the Department of Energy's NERI and Power Conversion Program under DOE Idaho Operations Office Contract DE-AC07-99ID13727.

REFERENCES

Aspen Technology, 2005a, "HYSYS Process Version 2.2.2," www.aspentech.com.

Copsey, B. et al., The Framatome ANP Indirect-Cycle Very High Temperature Reactor, Proceedings of ICAPP'04, Pittsburgh, PA, June 13-17, 2004.

Dostal V., M.J. Driscoll, P. Hejzlar, *A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors*, March 10, 2004, MIT-ANP-TR-100.

Oh, C. and R. Moore, Brayton Cycle for High-Temperature Gas-Cooled Reactors*," Nuclear Technology*, Vol. 149, March, 2005.

Wang C., *Design, Analysis and Optimization of the Power Conversion System for the Modular Pebble Bed Reactor System*, MIT Ph.D. Thesis, August 31, 2003.